List of Figures

Chapter Forty-four

VERTICAL ALIGNMENT

Chapter Forty-four presents the Department's criteria for the design of vertical alignment elements. This includes grades, climbing lanes, vertical curves and vertical clearances.

44-1.0 GRADES

44-1.01 Terrain (Definitions)

1. Level. Highway sight distances are either long or could be made long without major construction expense. The terrain is generally considered to be flat, which has minimal impact on vehicular performance.

2. Rolling. The natural slopes consistently rise above and fall below the roadway grade and, occasionally, steep slopes present some restriction to the desirable highway alignment. In general, rolling terrain generates steeper grades, causing trucks to reduce speeds below those of passenger cars.

3. Mountainous. Longitudinal and transverse changes in elevation are abrupt, and benching and side hill excavation are frequently required to provide the desirable highway alignment. Mountainous terrain aggravates the performance of trucks relative to passenger cars, resulting in some trucks operating at crawl speeds.

   In Indiana, the use of mountainous terrain criteria will not be allowed on Federal-aid projects because, even though a roadway may pass through a mountainous site, the area as a whole is still considered to be rolling terrain.

In general, if it is not clear which terrain designation to use (e.g., level versus rolling), the flatter of the two should be selected.

44-1.02 Maximum Grades

Chapters Fifty-three through Fifty-six present the Department criteria for maximum grades based on functional classification, urban/rural location, type of terrain, design speed and project scope of work. The maximum grades should be used only where absolutely necessary. Where practical, grades flatter than the maximum should be used.

44-1.03 Minimum Grades

The following provides the Department's criteria for minimum grades:

1. Uncurbed Roads. It is desirable to provide approximately a 0.5% longitudinal grade. This allows for the possibility that the original crown slope is subsequently altered as a result of swell, consolidation, maintenance operations or resurfacing. Level longitudinal gradients may be acceptable on pavements which are adequately crowned to drain laterally.

2. Curbed Streets. The centerline profile on highways and streets with curbs should desirably have a minimum longitudinal gradient of 0.5%. Flatter or even level grades with rolling curb lines may be necessary in level terrain, where the adjacent development precludes the taking of additional right-of-way.

   On curbed facilities, the longitudinal gradient at the gutter line will have a significant impact on the pavement drainage characteristics (e.g., ponding, flow capture by grated inlets or catch basins). See Part IV for more information on pavement drainage.

44-1.04 Critical Length of Grade

Critical length of grade is the maximum length of a specific upgrade on which a loaded truck can operate without an unreasonable reduction in speed. The highway gradient in combination with the length of grade will determine the truck speed reduction on upgrades. The following will apply to the critical length of grade:

1. Design Vehicle. A loaded truck, powered so that the mass/power ratio is about 120 kg/kW is representative of the size and type of vehicle normally used for design on major routes. For other highways, designing for the 120 kg/kW truck is not always cost-effective, especially on routes which have minimal truck traffic. Therefore, to better reflect the wide range of trucks, INDOT has adopted the following critical-length-of-grade criteria:

   a. Major Routes. The 15 km/h reduction curve in Figure 44-1A, Critical Length of Grade for Trucks, presents the critical length of grade for a 120 kg/kW truck. This figure should be used to determine the critical length of grade on all freeways, principal and minor arterials or for any projects on the extra heavy-duty highway system. See Chapter Sixty for a listing of extra heavy-duty routes. It also should be used on other road classifications where significant numbers of large trucks are known to use the facility (e.g., coal-hauling routes).

b. Other Routes. The 25 km/h reduction curve in Figure 44-1A presents the critical length of grade for single-unit trucks and the major portion of tractor-trailer trucks. Figure 44-1A can be used on all routes not identified in Item a. (e.g., collectors and local roads).

See Figure 44-1B, Critical Length of Grade for Recreational Vehicles.

2. Criteria. Figure 44-1A provides the critical lengths of grade for a given percent grade and acceptable truck speed reduction. This figure is based on an initial truck speed of 110 km/h, and representative truck (120 kg/kW).

3. Momentum Grades. Where an upgrade is preceded by a downgrade, trucks will often increase speed to make the climb. A speed increase of 10 km/h on moderate downgrades (3-5%) and 15 km/h on steeper downgrades (6-8%) of sufficient length are reasonable adjustments. These can be used in design to allow the use of a higher speed reduction curve in Figures 44-1A and 44-1B. However, the designer should consider that these speed increases may not be attainable if traffic volumes are high enough that a truck may be behind a passenger vehicle when descending the momentum grade. Therefore, these increases in speed can only be considered if the highway has a LOS C or better.

4. Measurement. Figures 44-1A and 44-1B are based upon length of tangent grade. If vertical curves are part of the length of grade, Figure 44-1C, Measurement for Length of Grade, illustrates how to determine an approximate equivalent tangent grade length.

5. Application. If the critical length of grade is exceeded, the designer should either flatten the grade, if practical, or should evaluate the need for a truck-climbing lane (see Section 44-2.0).

6. Highway Types. The critical length of grade criteria apply to 2-lane or multi-lane highways and to urban and rural facilities. Climbing lanes are not used as extensively on freeways and multilane facilities because they more frequently have sufficient capacity to handle their design year traffic without being congested. Vehicles can more easily move left to pass slower vehicles.

7. Example Problems. Examples 44-1.1 and 44-1.2 illustrate the use of Figure 44-1A to determine the critical length of grade. Example 44-1.3 illustrates the use of both Figures 44-

1B and 44-1C. In the examples, the use of subscripts 1, 2, etc., indicate the successive gradients and lengths of grade on the highway segment.

* * * * * * * * * *

Example 44-1.1

Given: Level Approach
$G = +4\%$
$L = 300$ m (length of grade)
Rural Arterial

Problem: Determine if the critical length of grade is exceeded.

Solution: Figure 44-1A yields a critical length of grade of 350 m for a 15-km/h speed reduction. The grade is acceptable (300 < 350).

Example 44-1.2

Given: Level Approach
$G_1 = +2\%$
$L_1 = 500$ m
$G_2 = +5\%$
$L_2 = 200$ m
Rural Collector with significant number of heavy trucks

Problem: Determine if the critical length of grade is exceeded for the combination of grades G_1 and G_2

Solution: Using Figure 44-1A, G_1 yields a truck speed reduction of 9 km/h. G_2 yields approximately 11 km/h. The total of 20 km/h is greater than the allowable 15 km/h. Therefore, the critical length of grade is exceeded.

Example 44-1.3

Given: Figure 44-1D, Critical Length of Grade Calculations (Example 44-1.3), illustrates the vertical alignment on a low-volume, 2-lane rural highway with no large trucks.

Problem: Determine if the critical length of grade is exceeded for G_2 or the combination upgrade G_3/G_4.

Solution: Figure 44-1C presents the criteria for determining the length of grade. These are calculated for this example as follows:

$$L_2 = \frac{300}{4} + 180 + \frac{260}{4} = 320\ m$$

$$L_3 = \frac{260}{4} + 200 + \frac{125}{2} = 328\ m$$

$$L_4 = \frac{125}{2} + 150 + \frac{240}{4} = 273\ m$$

Read into Figure 44-1B for G_2 (3%) and find a length of grade of 550 m. L_2 is less than this value and, therefore, the length of grade is not exceeded.

Read into Figure 44-1B for G_3 (3.5%) and L_3 = 328 m and find a speed reduction of 6 km/h. Read into Figure 44-1B for G_4 (2%) and L_4 = 273 m and find a speed reduction of 4 km/h. Therefore, the total speed reduction on the combination upgrade G_3/G_4 is 10 km/h. However, for low-volume roads, the designer may assume a 10-km/h increase in truck speed for the 3% "momentum" grade (G_2) which precedes G_3. Therefore, the speed reduction may be as high as 25 km/h before the combination grade exceeds the critical length of grade. Assuming the benefits of the momentum grade leads to the conclusion that the critical length of grade is not exceeded.

* * * * * * * * * *

44-2.0 CLIMBING LANES

44-2.01 Warrants

A climbing lane may be warranted for trucks and recreational vehicles to allow a specific upgrade to operate at an acceptable level of service. The following criteria will apply.

44-2.01(01) Two-Lane Highways

A climbing lane on a 2-lane, 2-way highway may be warranted if the following conditions are satisfied:

1. Upgrade traffic flow rate is in excess of 200 vehicles per hour.

2. Upgrade truck flow rate is in excess of 20 trucks per hour.

3. One of the following conditions exists:

   a. A 15 km/h or greater speed reduction is expected for a typical heavy truck.

   b. Level of Service (LOS) E or F exists on the grade.

   c. A reduction of two or more levels of service is experienced when moving from the approach segment to the grade.

The upgrade flow rate is determined by multiplying the design hour volume by the directional distribution factor for the upgrade direction and dividing the result by the peak hour factor. See AASHTO A Policy on Geometric Design of Highways and Streets for more information including where to begin and end climbing lanes.

Climbing lanes may also be warranted where the above criteria are not met if, for example, there is an adverse accident experience on the upgrade related to slow-moving trucks. However, on designated recreational routes, where a low percentage of trucks may not warrant a climbing lane, sufficient recreational-vehicle traffic may indicate a need for an additional lane. This can be evaluated by using Figure 44-1B, Critical Length of Grade for Recreational Vehicles. Climbing lanes must be designed for each direction, independently of the other.

44-2.01(02) Multi-Lane Highways

A climbing lane may be warranted on a multi-lane highway if the following conditions are satisfied:

1. the critical length of grade is less than the length of grade being evaluated; and

2. one of the following conditions exists:

   a. the LOS on the upgrade is E or F, or

   b. there is a reduction of one or more LOS when moving from the approach segment to the upgrade; and

3. the construction costs and the construction impacts (e.g., environmental, right-of-way) are considered reasonable.

Climbing lanes are generally not warranted on 4-lane facilities with directional volumes below 100 vehicles per hour per lane, regardless of the percentage of trucks. See AASHTO *A Policy on Geometric Design of Highways and Streets* for more information.

Climbing lanes may also be warranted where the above criteria are not met if, for example, there is an adverse accident experience on the upgrade related to slow-moving trucks.

44-2.02 Capacity Procedures

44-2.02(01) Two-Lane Highways

The objective of the capacity analysis procedure is to determine if the warranting criteria in Section 44-2.01 are met for 2-lane facilities. This is accomplished by calculating the service flow rate for each LOS level (A through D) and comparing this to the actual flow rate on the upgrade. Because a LOS worse than D warrants a climbing lane, it is not necessary to calculate the service flow rate for LOS E.

The designer should analyze the operations on the grade using the procedures in the *Highway Capacity Manual* (HCM). In addition, the designer should consider the following:

1. To calculate the LOS, the following data should be compiled to complete the analysis:

    a. average annual daily traffic (AADT) (mixed composition for year under design);

    b. the K factor (i.e., the proportion of AADT occurring in the design hour);

    c. the directional distribution (D) during the design hour (DHV);

    d. the truck factor (T) during the DHV (i.e., the % of trucks, buses and recreational vehicles);

    e. the peak-hour factor (PHF);

    f. the design speed;

    g. lane and shoulder widths (m);

    h. percent grade;

i. percent no-passing zones (based on the MUTCD criteria for striping of no-passing zones); see Chapter Seventy-six; and

j. length of grade (in km).

2. For 2-lane highways, the type of truck is not a factor in determining the passenger car equivalent. Only the proportion of heavy vehicles (i.e., trucks, buses and recreational vehicles) in the upgrade traffic stream is applicable.

3. For highways with a single grade, the critical length of grade can be directly determined from Figure 44-1A, Critical Length of Grade for Trucks, or Figure 44-1B, Critical Length of Grade for Recreational Vehicles. However, most highways have a continuous series of grades. Often, it is necessary to find the impact of a series of significant grades in succession. If several different grades are present, then a speed profile may need to be developed. Section 44-2.04 presents information on how to develop a truck speed profile.

44-2.02(02) Multi-Lane Highways

Climbing lanes on multi-lane highways are not as easily justified as those on 2-lane facilities because of the operational advantage of multi-lane highways; i.e., a passenger car can pass a slow-moving truck without occupying an opposing lane of travel. As indicated in Section 44-2.01, INDOT has adopted criteria to warrant a truck-climbing lane on multi-lane highways. These are based on the critical length of grade and on the LOS on the upgrade.

The calculation of LOS for an upgrade on multi-lane highways is similar to that on 2-lane highways (see Section 44-2.02(01) and the HCM). However, the various adjustment factors to calculate the service flow rate differ. This reflects the operational differences between multi-lane and 2-lane facilities. The designer should reference the *Highway Capacity Manual* for the detailed capacity methodology.

44-2.03 Design

See Figure 44-2A, Design Criteria for Climbing Lanes. The designer should also consider the following:

1. Design Speed. For design speeds equal to or greater than 90 km/h, use 90 km/h for truck design speed. For speeds less than 90 km/h, use the design speed.

2. Superelevation. For horizontal curves, the climbing lane will be superelevated at the same rate as the adjacent travel lane.

3. Performance Curves. Figure 44-2B, Performance Curves for Heavy Trucks (120 kg/kW) for Deceleration on Upgrades, presents the deceleration rates for heavy trucks. Figure 44-2C, Speed-Distance Curves for Acceleration of a Typical Heavy Truck (120 kg/kW on Upgrades and Downgrades), presents the acceleration rates for heavy trucks.

4. End of Full-Width Lane. In addition to the criteria in Figure 44-2A, the designer should consider the available sight distance to the point where the truck will merge back into the through travel lane. At a minimum, this will be stopping sight distance. Desirably, the driver should have decision sight distance available to the merge point at the end of the taper to safely complete the maneuver, especially where the merge is on a horizontal or vertical curve.

44-2.04 Truck Speed Profile

The following example illustrates how to construct a truck speed profile and how to use Figures 44-2B and 44-2C.

* * * * * * * * * *

Example 44-2.1

Given: Level Approach
G_1 = +3% for 250 m (PVI to PVI)
G_2 = +5% for 1000 m (PVI to PVI)
G_3 = -2% beyond the composite upgrade (G_1 and G_2)
V = 100 km/h (design speed)
Rural Arterial on a Heavy Truck Route

Problem: Using the criteria in Figure 44-2A and Figure 44-2B, construct a truck speed profile and determine the beginning and ending points of the full-width climbing lane.

Solution: The following steps apply:

Step 1: Determine the beginning of the full-width climbing lane. From Figure 44-2A, desirably the beginning of the full-width lane will begin at the PVC and, at a minimum, at the PVT.

Step 2: Determine the truck speed on G_1, at 100-m increments, using Figure 44-2B and plot them in Figure 44-2D. Assume an initial truck speed of 90 km/h (see Figure 44-2B).

Distance From PVI_1 (m)	Horizontal Distance on Figure 44-2B (m)	Truck Speed (km/h)	Comments
0	0	90	PVI_1
100	100	86	
200	200	82	
250	250	80	PVI_2

Step 3: Determine the truck speed on G_2, at 100-m increments, using Figure 44-2B and plot them in Figure 44-2D, Truck Speed Profile (Example 44-2.1). From Step 2, the initial speed on G_2 is the final speed from G_1 (i.e., 80 km/h). Move left horizontally along the 80 km/h line to the 5% upgrade. This is approximately 125 m along the horizontal axis. This is the starting point for G_2.

Distance From VPI_1 (m)	Horizontal Distance on Figure 44-2B (m)	Truck Speed (km/h)	Comments
250	125	80	PVI_2
350	225	73	
450	325	65	
550	425	57	
650	525	49	
750	625	42	
850	725	36	
950	825	33	
1050	925	31	
1150	1025	30 (1)	
1250	1125	30 (1)	PVI_3

(1) The final crawl speed of the truck for a 5% upgrade.

Step 4: Determine the truck speed on G_3, at 100-m increments using Figure 44-2B until the point where the truck is able to accelerate to 75 km/h (minimum design speed for ending the climbing lane) and plot them in Figure 44-2D. The truck will have a speed of 30 km/h as it enters the 2% downgrade at the PVI_3. Read into Figure 44-2B at the 30 km/h point on the vertical axis over to the -2% line. This is approximately 100 m along the horizontal axis. The -2% line is followed to 75 km/h, which is approximately 600 m along the horizontal axis. Therefore, the truck will require 500 m (600 m - 100 m) from the PVI_3 to reach 75 km/h. The truck will require approximately an additional 400 m to reach 90 km/h (the desirable criteria).

Distance From PVI_1 (m)	Horizontal Distance on Figure 44-2B (m)	Truck Speed (km/h)	Comments
1250	100	30	PVI_3
1350	200	47	
1450	300	56	
1550	400	65	
1650	500	71	
1750	600	75	Minimum End
1850	700	80	
1950	800	84	
2050	900	88	
2150	1000	90	Desirable End

44-3.0 VERTICAL CURVES

44-3.01 Crest Vertical Curves

Crest vertical curves are in the shape of a parabola. The basic equations for determining the minimum length of a crest vertical curve are as follows:

If the stopping sight distance is less than the vertical curve length,

$$L = \frac{AS^2}{200(\sqrt{h_1} + \sqrt{h_2})^2} = \frac{AS^2}{658} \qquad \text{(Equation 44-3.1)}$$

$$L = KA \qquad \text{(Equation 44-3.1A)}$$

If the stopping sight distance is greater than or equal to the vertical curve length,

$$L = 2S - \frac{658}{A} \qquad \text{(Equation 44-3.2A)}$$

where:

L	=	length of vertical curve, m
A	=	algebraic difference between the two tangent grades, %
S	=	stopping sight distance, m
h_1	=	height of eye above road surface, 1.08 m
h_2	=	height of object above road surface, 0.6 m
K	=	horizontal distance needed to produce a 1% change in gradient

The length of the crest vertical curve will depend upon A for the specific curve and upon the selected sight distance, height of eye and height of object. The following sections discuss the selection of these values.

44-3.01(01) Stopping Sight Distance

The principal control in the design of crest vertical curves is to ensure that, at a minimum, stopping sight distance (SSD) is available throughout the curve. Figure 44-3A, K-Values for Crest Vertical Curves Stopping Sight Distance - Passenger Cars), presents K-values for various design speeds when $S < L$. The following discusses the application of the K-values.

1. Passenger Cars (Level Grade). The minimum values are calculated by assuming $h_1 = 1080$ mm, $h_2 = 600$ mm and S = SSD in the basic equation for crest vertical curves (Equation 44-3.1). The minimum values represent the lowest acceptable sight distance on a facility. However, the designer should make every reasonable effort to provide a design in which the K-values are greater than the minimum, wherever practical.

   If the vertical curve length is less than the stopping sight distance, the designer may use any of the following methods to check the stopping sight distance.

   a. Using K-values. K provided $\geq$ K required and there are no changes to G1 or G2 as shown below.

   b. Using equation. The following equation is only valid if there are no other vertical curves or angular breaks in the area shown in Figure 44-3A.

   $$L = 2S - \frac{658}{A}$$

   c. Using the AASHTO *Policy on Geometric Design of Highways and Streets*.

   d. Checking graphically. Place the eye at 1080 mm above the pavement and the height of the object at 600 mm. The distance between the eye and the object that is unobstructed (by the road, backslope of a cut section, guardrail, etc.) is the stopping sight distance provided. It is necessary to check it in both directions for 2-lane highways.

If the length of the vertical curve is less than the stopping sight distance, and the stopping sight distance provided exceeds that required (even though the K provided is less than K required), the K value will be treated as a Level 3 Design Exception item instead of Level 1.

2 Trucks. On vertical curves, the higher eye height for trucks (i.e., 2330 mm) offsets their longer stopping distances. Therefore, the designer is not required to check the K-values for truck stopping sight distances.

3. Minimum Length. The minimum length of a crest vertical curve in meters should be 0.6V, where V is the design speed in km/h, unless existing conditions make it impractical to use the minimum length criteria.

44-3.01(02) Decision Sight Distance

At some locations, it may be warranted to provide decision sight distance in the design of crest vertical curves. Section 42-2.0 discusses candidate sites and provides design values for decision sight distance. These S values should be used in the basic equation for crest vertical curves (Equation 44-3.1). In addition, the following will apply:

1. Height of Eye (h_1). For passenger cars, h_1 is 1080 mm.

2. Height of Object (h_2). Decision sight distance, in many cases, is predicated upon the same principles as stopping sight distance; i.e., the driver needs sufficient distance to see a 600 mm object.

3. Passenger Cars. Figure 44-3B, K-Values for Crest Vertical Curves (Decision Sight Distance - Passenger Cars), presents the K-values using the decision sight distances presented in Section 42-2.0.

44-3.01(03) Drainage

Drainage should be considered in the design of crest vertical curves where curbed sections or concrete barriers are used. Drainage problems should not be experienced if the vertical curvature is sharp enough so that a minimum longitudinal grade of at least 0.3% is reached at a point about 15 m from either side of the apex. To ensure that this objective is achieved, the length of the vertical curve should be based upon a K-value of 51 or less. For crest vertical curves on curbed sections where this K-value is exceeded, the drainage design should be more carefully evaluated near the apex.

For uncurbed sections of highway, drainage should not be a problem at crest vertical curves. However, it is desirable to provide a longitudinal gradient of at least 0.15% at points about 15 m on either side of the high point. To achieve this, K must equal 100 or less.

See Part IV for more information on drainage.

44-3.02 Sag Vertical Curves

Sag vertical curves are in the shape of a parabola. Typically, they are designed to allow the vehicular headlights to illuminate the roadway surface (i.e., the height of object = 0.0 mm) for a given distance S. A headlight height of 600 mm and a 1-deg upward divergence of the light beam from the longitudinal axis of the vehicle are assumed. These assumptions yield the following basic equations for determining the minimum length of sag vertical curves. If $S \leq L$:

$$L = \frac{AS^2}{120 + 3.5S} \qquad \text{(Equation 44-3.3)}$$

If $S > L$:

$$L = 2S - \frac{120 + 3.5S}{A} \qquad \text{(Equation 44-3.4)}$$

where:

L	=	length of vertical curve, m
A	=	algebraic difference between the two tangent grades, %
S	=	sight distance, m
h_3	=	height of headlights above pavement surface, 0.6 m
K	=	horizontal distance needed to produce a 1% change in gradient

The length of the sag vertical curve will depend upon A for the specific curve and upon the selected sight distance and headlight height. The following sections discuss the selection of these values.

44-3.02(01) Stopping Sight Distance

The principal control in the design of sag vertical curves is to ensure that, at a minimum, stopping sight distance (SSD) is available for headlight illumination throughout the curve. Figure 44-3C, K-Values for Sag Vertical Curves (Stopping Sight Distance - Passenger Cars), presents K-values for various design speeds where S < L. The following discusses the application of the K-values.

1. Passenger Cars. These K-values are calculated by assuming h_3 = 600 mm and S = SSD in the basic equation for sag vertical curves (Equation 44-3.3). The values represent the lowest acceptable sight distance on a facility. However, the designer should make every reasonable effort to provide a design in which the K-values are greater than the values shown, wherever practical.

2. Trucks. The higher headlight height for trucks (i.e., 1200 mm) offsets their longer stopping distances on vertical curves. Therefore, the designer is not required to check the K-values for truck stopping sight distances.

3. Minimum Length. The minimum length of a sag vertical curve in meters should be 0.6V, where V is the design speed in km/h, unless existing conditions make it impractical to use the minimum length criteria.

   One exception to this minimum length on sag vertical curves may apply in curbed sections. If the sag is in a "sump," the use of the minimum length criteria may produce longitudinal slopes too flat to drain the stormwater without exceeding the criteria for the limits of ponding on the travel lane. See Part IV for more discussion on drainage.

44-3.02(02) Decision Sight Distance

At some locations, it may be warranted to provide decision sight distance in the design of sag vertical curves. Section 42-2.0 discusses candidate sites and provides design values for decision sight distance. These "S" values should be used in the basic equation for sag vertical curves (Equation 44-3.3). The height of headlights (h_3) is 600 mm. Figure 44-3D, K-Values for Sag Vertical Curves (Decision Sight Distance - Passenger Cars), provides K-values using decision sight distance.

44-3.02(03) Drainage

Drainage should be considered in the design of sag vertical curves where curbed sections or concrete barriers are used. Drainage problems are minimized if the sag vertical curve is sharp enough so that both of the following criteria are met:

1. a minimum longitudinal grade of at least 0.3% is reached at a point about 15 m from either side of the low point, and

2. there is at least a 100-mm elevation differential between the low point in the sag and the two points 15 m to either side of the low point.

To ensure that the first objective is achieved, the length of the vertical curve should be based upon a K-value of 51 or less. For sag vertical curves on curbed sections where this K-value is exceeded, the drainage design should be more carefully evaluated near the low point. For example, it may be necessary to install flanking inlets on either side of the low point.

For uncurbed sections of highway, drainage should not be a problem at sag vertical curves. However, it is desirable to provide a longitudinal gradient of at least 0.15% at points about 15 m on either side of the low point. To achieve this, K must equal 100 or less.

See Part IV for more information on drainage.

44-3.02(04) Sight Distance at Undercrossings

Sight distance on a highway through a grade separation should be at least as long as the minimum stopping sight distance and preferably longer. Design of the vertical alignment is the same at any other point on the highway except in some cases of sag vertical curves underpassing a structure, as shown in Figure 44-3D, K-Values for Sag Vertical Curves (Decision Sight Distance - Passenger Cars). While not a frequent problem, the structure fascia may cut the line of sight and limit the sight distance to less than that otherwise attainable. It is generally practical to provide the minimum length of sag vertical curve at a grade separation structure. Even where the recommended grades are exceeded, the sight distance should not need to be reduced below the minimum values for stopping sight distance.

For some conditions, the designer may wish to check the available sight distance at an undercrossing, such as with two lanes without ramps, where it would be desirable to provide passing sight distance. Such checks are best made graphically on the profile, but may be performed through computations.

The general equations for sag vertical curve length at undercrossings are as follows:

1. Sight distance greater than length of vertical curve (S > L)

$$L = 2S - \left\{ \frac{800[C - 0.5(h_1 + h_2)]}{A} \right\} \qquad \text{(Equation 44-3.5)}$$

2. Sight distance less than or equal to length of vertical curve ($S \leq L$)

$$L = \frac{AS^2}{800\,[C - 0.5(h_1 + h_2)]} \qquad \text{(Equation 44-3.6)}$$

For both equations, where:

L = length of vertical curve, m
S = sight distance, m
A = algebraic difference in grades, %
C = vertical clearance, m
h_1 = height of eye, m
h_2 = height of object, m

Using an eye height of 2.4 m for a truck driver and an object height of 0.6 m for the taillights of a vehicle, the following equation can be derived.

3. Sight distance greater than length of vertical curve (S > L)

$$L = 2S - \frac{800(C - 1.5)}{A} \qquad \text{(Equation 44-3.7)}$$

4. Sight distance less than or equal to length of vertical curve ($S \leq L$)

$$L = \frac{AS^2}{800(C - 1.5)} \qquad \text{(Equation 44-3.8)}$$

44-3.03 Vertical Curve Computations

The following will apply to the mathematical design of vertical curves:

1. Definitions. Figure 44-3E, Vertical Curve Definitions, presents the common terms and definitions used in vertical curve computations.

2. Measurements. All measurements for vertical curves are made on the horizontal or vertical plane, not along the profile grade. With the simple parabolic curve, the vertical offsets from the tangent vary as the square of the horizontal distance from the PVC or PVT. Elevations along the curve are calculated as proportions of the vertical offset at the vertical point of intersection (PVI). The necessary formulas for computing the vertical curve are shown in Figure 44-3F, Symmetrical Vertical Curve Equations. Figure 44-3G, Vertical Curve Computations (Example 44-3.1), provides an example of how to use these formulas.

3. Unsymmetrical Vertical Curve. Occasionally it is necessary to use an unsymmetrical vertical curve to obtain clearance on a structure or to satisfy some other design feature. This curve is similar to the parabolic vertical curve, except the curve does not vary symmetrically about the PVI. The necessary formulas for computing the unsymmetrical vertical curve are shown in Figure 44-3H, Unsymmetrical Vertical Curve Equations.

4. Vertical Curve Through Fixed Point. A vertical highway curve often must be designed to pass through an established point. For example, it may be necessary to tie into an existing transverse road or to clear existing structures. See Figure 44-3 I, Vertical Curve Computations. Figure 44-3J, Vertical Curve Computations (Example 44-3.2), illustrates an example on how to use these formulas.

44-4.0 VERTICAL CLEARANCES

See Figure 44-4A, Minimum Vertical Clearances (New Construction/ Reconstruction). Chapter Fifty-three provides additional information. Chapters Fifty-four through Fifty-six provide vertical clearance information for existing highways.

44-5.0 DESIGN PRINCIPLES AND PROCEDURES

44-5.01 General Controls for Vertical Alignment

As discussed elsewhere in Chapter Forty-four, the design of vertical alignment involves, to a large extent, complying with specific limiting criteria. These include maximum and minimum grades, sight distance at vertical curves and vertical clearances. In addition, the designer should adhere to certain general design principles and controls which will determine the overall safety of the facility and will enhance the aesthetic appearance of the highway. These design principles for vertical alignment include:

1. Consistency. Use a smooth grade line with gradual changes, consistent with the type of highway and character of terrain, rather than a line with numerous breaks and short lengths of tangent grades.

2. Environmental Impacts. Vertical alignment should be properly coordinated with environmental impacts (e.g., encroachment onto wetlands). The Pre-Engineering and Environment Division is responsible for evaluating environmental impacts.

3. Long Grades. On a long ascending grade, it is preferable to place the steepest grade at the bottom and flatten the grade near the top.

4. Intersections. Maintain moderate grades through intersections to facilitate turning movements. See Chapter Forty-six for specific information on vertical alignment through intersections.

5. Roller Coaster. The "roller-coaster" type of profile should be avoided. They may be proposed in the interest of economy, but they are aesthetically undesirable and may be hazardous.

6. Broken-Back Curvature. Avoid "broken-back" grade lines (two crest or sag vertical curves separated by a short tangent). One long vertical curve is more desirable.

7. Coordination with Natural/Man-Made Features. The vertical alignment should be properly coordinated with the natural topography, available right-of-way, utilities, roadside development and natural/man-made drainage patterns.

8. Cut Sections. Sag vertical curves should be avoided in cuts unless adequate drainage can be provided.

44-5.02 Coordination of Horizontal and Vertical Alignment

Horizontal and vertical alignment should not be designed separately, especially for projects on new alignment. Their importance demands that the designer carefully evaluate the interdependence of the two highway design features. This will enhance highway safety and improve the facility's operation. The following should be considered in the coordination of horizontal and vertical alignment:

1. Balance. Curvature and grades should be in proper balance. Maximum curvature with flat grades or flat curvature with maximum grades does not achieve this desired balance.

A compromise between the two extremes produces the best design relative to safety, capacity, ease and uniformity of operations and a pleasing appearance.

2. <u>Coordination</u>. Vertical curvature superimposed upon horizontal curvature (i.e., vertical and horizontal PIs at approximately the same stations) generally results in a more pleasing appearance and reduces the number of sight distance restrictions. Successive changes in profile not in combination with the horizontal curvature may result in a series of humps visible to the driver for some distance, which may produce an unattractive design. However, under some circumstances, superimposing the horizontal and vertical alignment must be tempered somewhat by Items 3 and 4 as follows.

3. <u>Crest Vertical Curves</u>. Sharp horizontal curvature should not be introduced at or near the top of pronounced crest vertical curves. This is undesirable because the driver cannot perceive the horizontal change in alignment, especially at night when headlight beams project straight ahead into space. This problem can be avoided if the horizontal curvature leads the vertical curvature or by using design values which well exceed the minimums.

4. <u>Sag Vertical Curves</u>. Sharp horizontal curves should not be introduced at or near the low point of pronounced sag vertical curves or at the bottom of steep vertical grades. Because visibility to the road ahead is foreshortened, only flat horizontal curvature will avoid an undesirable, distorted appearance. At the bottom of long grades, vehicular speeds often are higher, particularly for trucks, and erratic operations may occur, especially at night.

5. <u>Passing Sight Distance</u>. In some cases, the need for frequent passing opportunities and a higher percentage of passing sight distance may supersede the desirability of combining horizontal and vertical alignment. In these cases, it may be necessary to provide long tangent sections to secure sufficient passing sight distance.

6. <u>Intersections</u>. At intersections, horizontal and vertical alignment should be as flat as practical to provide designs which produce sufficient sight distance and gradients for vehicles to slow or stop. See Chapter Forty-six.

7. <u>Divided Highways</u>. On divided facilities with wide medians, it is frequently advantageous to provide independent alignments for the two one-way roadways. Where traffic justifies a divided facility, a superior design with minimal additional cost generally can result from the use of independent alignments.

8. <u>Residential Areas</u>. The alignment should be designed to minimize nuisance factors to neighborhoods. Generally, a depressed facility makes the highway less visible and reduces the noise to adjacent residents. Minor adjustment to the horizontal alignment may increase the buffer zone between the highway and residential areas.

9. Aesthetics. The alignment should be designed to enhance attractive scenic views of rivers, rock formations, parks, golf courses, etc. The highway should head into rather than away from those views that are considered to be aesthetically pleasing. The highway should fall towards those features of interest at a low elevation and rise toward those features which are best seen from below or in silhouette against the sky.

44-5.03 Profile Grade Line

44-5.03(01) General

The profile grade line is perhaps the roadway geometric characteristic which has the greatest impact on a facility's costs, aesthetics, safety and operation. The profile grade is a series of tangent lines connected by parabolic vertical curves. It is typically placed along the roadway centerline of undivided facilities and at the two pavement centerlines on divided facilities.

The designer must carefully evaluate many factors when establishing the profile grade line. These include:

1. maximum and minimum gradients;
2. sight distance criteria;
3. earthwork balance;
4. bridges and drainage structures;
5. high water levels;
6. drainage considerations;
7. water table elevations;
8. highway intersections and interchanges;
9. snow drifting;
10. railroad/highway crossings;
11. types of soil;
12. adjacent land use and values;
13. highway safety;
14. coordination with other geometric features (e.g., cross section);
15. topography/terrain;
16. truck performance;
17. right-of-way;
18. utilities;
19. urban/rural location;
20. aesthetics/landscaping;
21. construction costs.;
22. environmental impacts;

23. driver expectations;
24. airport flight paths (e.g., grades and lighting); and
25. pedestrian and handicapped accessibility.

The following sections discuss the establishment of the profile grade line in more detail.

44-5.03(02) Earthwork Balance

Where practical and where consistent with other project objectives, the designer should design the profile grade line to provide a balance of earthwork. This should not be achieved, however, at the expense of smooth grade lines and sight distance requirements at vertical curves. Ultimately, a project-by-project assessment will determine whether a project will be borrow, waste or balanced.

The following should be considered in earthwork balance:

1. Basic Approach. The best approach to laying grade and balancing earthwork is to provide a significant length of roadway in embankment, to limit the number and amount of excavation areas. The designer should, as practical, avoid long lengths of roadway in excavation and avoid several short balance distances.

2. Urban/Rural. Earthwork balance is typically a practical objective only in rural areas. In urban areas, other project objectives (e.g., limiting right-of-way impacts) typically have a higher priority than balancing earthwork. In addition, excavated materials from urban projects are often unsuitable for embankments.

3. Borrow Sites. The availability and quality of borrow sites in the vicinity of the project will impact the desirability of balancing the earthwork.

4. Mass Diagram. A mass diagram illustrates the accumulated algebraic sum of material between project limits. These diagrams are useful in balancing earthwork and calculating haul distances and quantities. The mass diagram may indicate:

    a. the most economical procedure for disposing of excavated material,

    b. whether material should be moved backward or forward, or

    c. whether borrowing or wasting is more economical than achieving earthwork balance.

Typically, mass diagrams are not prepared by the designer; however; they may be prepared and used by contractors for construction operation.

5. Balance Lengths. Typical balance lengths are 600 m or longer. For interchanges, balance points should be selected to incorporate the entire interchange.

6. Earthwork Computations. Chapter Seventeen discusses the proper methods to compute and record the project earthwork quantities.

44-5.03(03) Soils

The type of earth material encountered often influences the grade line at certain locations. If rock is encountered, for example, it may be more economical to raise the grade and reduce the rock excavation. Soils which are unsatisfactory for embankment or cause a stability problem in cut areas may also be determining factors in establishing a grade line. The designer should coordinate the development of the profile grade with the Materials and Tests Division which will conduct a soils survey.

44-5.03(04) Drainage/Snow

The profile grade line should be compatible with the roadway drainage design and should minimize snow drift problems. The following will apply:

1. Culverts. The roadway elevation should meet the Department criteria for minimum cover at culverts and minimum freeboard above the head water level at culverts. See Part IV for more information on culvert designs.

2. Coordination with Geometrics. The profile grade line must reflect compatibility between drainage design and roadway geometrics. These include the design of sag and crest vertical curves, spacing of inlets on curbed facilities, impacts on adjacent properties, superelevated curves, intersection design elements and interchange design elements. For example, the designer should avoid placing sag vertical curves in cuts and placing long crest vertical curves on curbed pavements.

3. Snow Drifting. Where practical, the profile grade line should be at least 1.0 m above the natural ground level to prevent snow from drifting onto the roadway and to promote snow blowing off the roadway.

4. Water Tables. The profile grade line should be established such that the top of the subgrade elevation should be not less than 0.6 m above the water table at all points along any cross section within the paved roadway surface. The elevation of the water table typically can be found in the soils report. If it is not practical to provide the 0.6-m clearance, the designer should meet with the Materials and Tests Division's pavement design engineer and geotechnical engineer to develop an alternative solution.

44-5.03(05) Erosion Control

To minimize erosion, the designer should consider the following relative to the grade line.

1. Minimize the number of deep cuts and high fill sections.

2. Conform to the contour and drainage patterns of the area.

3. Make use of natural land barriers and contours to divert runoff and confine erosion and sedimentation.

4. Minimize the amount of disturbance.

5. Make use of existing vegetation.

6. Reduce slope length and steepness and ensure that erosion is confined to the right-of-way and does not deposit sediment on or erode away adjacent land.

7. Avoid locations having high base erosion potential.

8. Avoid cut or fill sections in seepage areas.

44-5.03(06) Bridges

The design of profile grade lines must be carefully coordinated with any bridges within the project limits. The following will apply:

1. Vertical Clearances. The criteria in Chapters Fifty-three and Fifty-six and Section 44-3.0 must be met. When laying the preliminary grade line, an important element in determining available vertical clearance is the assumed structure depth. This will be based on the structure type, span lengths and depth/span ratio. For preliminary design, the designer should assume a 6.2-m to 6.5-m distance between the finished grade of the

roadway and the finished grade of the bridge deck. For final design, the designer must coordinate with the bridge designer to determine the roadway and bridge grade lines.

2. Bridges Over Water. Where the proposed facility will cross bodies of water, the bridge elevation must be consistent with the necessary waterway opening to meet the Department's hydraulic requirements. The designer must coordinate with the Design Division's Hydraulics Unit and bridge designer to determine the approach roadway elevation to meet the necessary bridge elevation.

3. Railroad Bridges. Any proposed facilities over railroads must meet the applicable criteria (e.g., vertical clearances, structure type and depth). See Chapter Sixty-nine for more information.

4. Highway Under Bridge. Where practical, the low point of a roadway sag vertical curve should not be within the shadow of the bridge. This will help minimize ice accumulations, and it will reduce the ponding of water which may weaken the earth foundation beneath the bridge. To achieve these objectives, the low point of a roadway sag should be approximately 30 m from the bridge.

5. High Embankments. The designer should consider the impacts of high embankments on structures. This will increase the span length thus increasing structure costs.

6. Low Point. It is desirable to locate the low point of a sag vertical curve off the bridge deck.

44-5.03(07) Distance Between Vertical Curves

A desirable objective on rural facilities is to provide at least 500 m between two successive PVIs. This objective only applies to projects which have a considerable length where implementation is judged to be practical.

44-5.03(08) Ties with Existing Highways

A smooth transition is needed between the proposed profile grade line of the project and the existing grade line of an adjacent highway section. Existing grade lines should be considered for a sufficient distance beyond the beginning and end of a project to ensure adequate sight distance. Connections should be made which are compatible with the design speed of the new project and which can be used if the adjoining road section is reconstructed.